

14p  
NASA TECHNICAL TRANSLATION

NASA TT F-15,311

WIND ENERGY: ITS VALUE AND THE CHOICE OF SITE FOR EXPLOITATION

P. Ailleret

(NASA-TT-F-15311) WIND ENERGY: ITS  
VALUE AND THE CHOICE OF SITE FOR  
EXPLOITATION (Kanner (Leo) Associates)  
20 p HC CSCL 10A

N74-15734

Unclas  
27517

G3/03

Translation of "l'Energie éolienne: sa valeur et la pros-  
pection des sites," Revue générale de l'électricité,  
vol. 55, March 1946, pp. 103-108.

Reproduced by  
NATIONAL TECHNICAL  
INFORMATION SERVICE  
US Department of Commerce  
Springfield, VA. 22151



NATIONAL AERONAUTICS AND SPACE ADMINISTRATION  
WASHINGTON, D.C. 20546 JANUARY 1974

1. Report No. NASA TT F-15,311	2. Government Accession No.	3. Recipient's Catalog No.	
4. Title and Subtitle WIND ENERGY: ITS VALUE AND THE CHOICE OF SITE FOR EXPLOITATION		5. Report Date January 1974	
		6. Performing Organization Code	
7. Author(s) P. Ailleret		8. Performing Organization Report No.	
		10. Work Unit No.	
9. Performing Organization Name and Address Leo Kanner Associates Redwood City, California 94063		11. Contract or Grant No. NASW-2481	
		13. Type of Report and Period Covered Translation	
12. Sponsoring Agency Name and Address National Aeronautics and Space Adminis- tration, Washington, D.C. 20546		14. Sponsoring Agency Code	
15. Supplementary Notes Translation of "l'Energie éolienne: sa valeur et la prospection des sites," <u>Revue générale de l'électricité</u> , vol. 55, March 1946, pp. 103-108.			
16. Abstract The problem of wind power utilization is discussed, includ- ing determination of wind power per square meter obtained yearly from surfaces subjected to wind action, and systematic prospecting for favorable sites using a simple anemometric device which calculates wind speed with the aid of a special electric meter.  A description is given of a program for site selection which has been approved by the Technical Committee on Wind Energy, which will make it possible to determine the energy which can be produced by the wind engines used.			
17. Key Words (Selected by Author(s))		18. Distribution Statement  Unclassified-Unlimited	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 18 20	22.

# WIND ENERGY; ITS VALUE AND THE CHOICE OF SITE FOR EXPLOITATION

## P. Ailleret

### I. INTRODUCTION

There is no doubt that considerable amounts of energy can be obtained from wind power: the value of this power can be as high as a thousand kilowatthours per year per square meter of surface exposed to wind.

/103\*

However, it is impossible to say at this point whether or not the use of this energy is economically feasible. To facilitate an answer to this question the problem may be divided into two parts: (1) determination of the cost of a wind engine per square meter of surface subjected to wind; (2) determination of the energy value which may be extracted annually per square meter of surface subjected to wind.

The present study will be concerned solely with this second problem.

### II. The Cubic Principle

Wind power is proportional to the cube of the wind speed. It is equal to the product of the flow rate, proportional to the speed, times the kinetic energy per unit volume, proportional to the square of the speed. For this reason this type of power is extremely variable in time. It is also extremely variable in space: wind speeds may easily vary from one site to another by a factor of two; the energy producible by a single wind engine will thus vary on a ratio of one to eight, indicating that an installation may be perfectly viable at one site and an economic disaster at another.

---

\*Numbers in the margin indicate pagination in the foreign text.

### III. The Quality of Wind Energy

Let us first determine the "quality" of the energy produced. Everyone knows that wind is variable; this variability, however, must be analyzed on different time scales:

On a one-second scale, variations arising from wind disturbances present problems in wind engine design which are relatively well-known and which will not be dealt with here.

On a ten-second or one-minute scale, the variations may at times be small and at other times extremely large; both regular and highly turbulent winds may be encountered at a single location.

On a power graph, that is a graph of the wind speeds cubed, the amplitude of modulation in the average power of the wind because of turbulence will obviously be considerable. One can immediately see the difficulties involved in using meteorological measurements of average wind speeds, since for a variable wind the average speed cubed will differ considerably from the average speed.

These variations pose difficult problems in the capture of wind energy, since the wind engine must be able to adapt itself to the wind instantaneously.

Once the energy has left the device in the form of electricity, there is a further problem in regard to the quality of the energy distributed over a large network. Variations in the wind may produce regulatory technical difficulties for the French network as a whole; but only minor economic problems are involved here, at least as long as the total power of the wind engines remains low in relation to the total power of hydroelectric units,

and on the same order as the "nodes" of the overall charge of the network.<sup>1</sup> For the first hundred thousand kilowatts supplied by wind engines the economic effect of these variations on the amount /104 of power produced will be negligible, and, given statistical compensation, it is possible that serious economic disadvantages will occur only at extremely high power levels. (in the same way that variations in the power supplied to customers are of slight importance in relation to the cost price of the energy supplied by a large network).

On a one-hour scale this phenomenon develops more economic importance, since, independent of chance variations which may be compensated by an appropriate modulation in the power coming from the top layers of even the lowest water reserves, systematic daily variations may be noted which may affect the energy value.

At high altitudes the wind is stronger at night than during the day, but heating of the ground by the sun stirs the air in a vertical direction, making it easier during the day for high atmospheric layers to pull the layers close to the ground. For this reason variations may occur near the ground, where the energy appears to be higher during the day than at night.

Hourly variations must therefore be carefully examined for each site, even though no definite a priori information can be offered; nevertheless it does not appear that there should be any great overall difference in the energy value from day to night.

Variations from one-day to the next may have considerable

---

1. These "nodes," measured by the instantaneous oscillations of the consumption curve around its mean profile, are on the order of 50,000 to 100,000 kW for the overall charge of the French network.

importance from the standpoint of the energy value produced.

If one accepts monthly averages, the seasonal distribution of wind would appear to be relatively favorable, as can be seen from the graph shown in Fig. 1, which gives the monthly averages for ten locations over a period of one year.

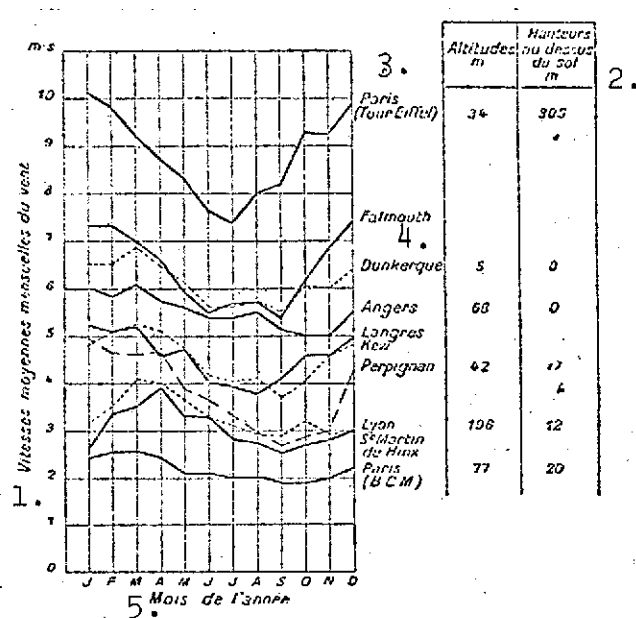


Fig. 1. Curves of monthly variations in average wind speed.

Key:

1. Average monthly wind speed.
2. Elevation.
3. Paris (Eiffel Tower).
4. Dunkirk.
5. Month of the year.

Although some reservations must be made since the arithmetic averages differ considerably from the cubed averages, a family of power curves (speeds cubed) (Fig. 2) has been established for each month for the Eiffel Tower site, and this confirms and reinforces the projected conclusion on linear means: the energy available during the winter months is approximately double the energy available during the summer.

This favorable correlation with seasonal variations in human energy requirements is an important element in the value of wind energy.

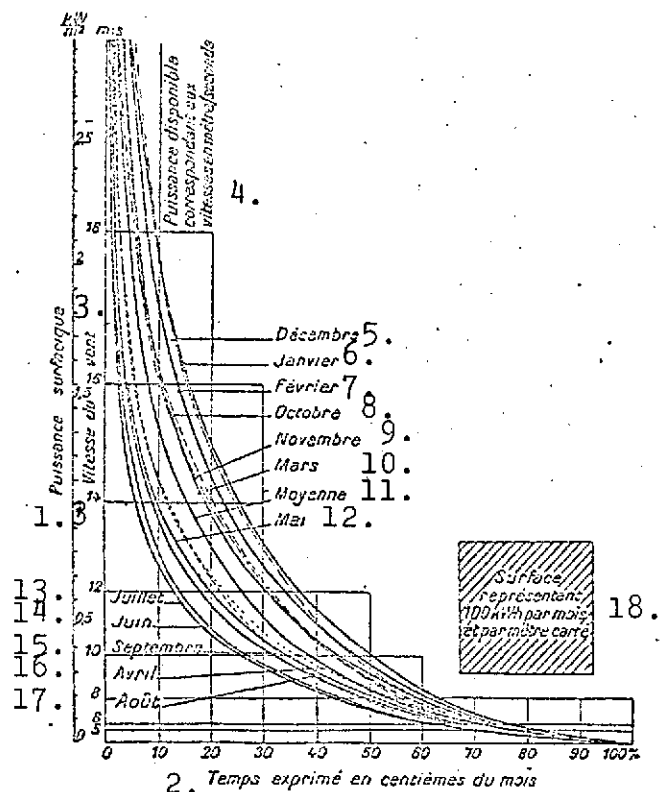


Fig. 2. Curves of frequency of available power measured at the top of the Eiffel Tower. The values for the surface power of the wind, in kilowatts per square meter, have been determined using the

formula  $P = 0.37 \left( \frac{V}{10} \right)^3 \text{ kW : m}^2$ , in which V

is expressed in meters per second.

- |      |  |  |
|------|--|--|
| Key: | 1. Surface power.  | 10. March.   |
|      | 2. Time expressed in hundredths of months.                       | 11. Mean.  |
|      | 3. Wind speed.   | 12. May.   |
|      | 4. Available power corresponding to speeds in meters per second. | 13. July.  |
|      | 5. December.   | 14. June.  |
|      | 6. January.  | 15. September.   |
|      | 7. February.   | 16. April.   |
|      | 8. October.  | 17. August.  |
|      | 9. November.   | 18. Surface representing 100 kWh per square meter per month. |

The average year never actually occurs, however, and a more detailed study of wind variations must be made in a country such as France, where a large part of the energy consumed is produced by hydroelectric plants capable of energy accumulation. The "quality" of wind energy differs considerably a priori, according to whether or not its variations on a weekly scale are compensated for by the certainty of being able to rely on a statistical energy minimum during periods when energy reserves are being used, that is, during periods of about two to three months. Moreover, the amount of wind energy will not be the same if the periods of abundant wind energy are identical in all areas, or if different areas compensate for each other because of differences in wind systems.

Theoretically, according to meteorological data large depressions extend over enormous surface areas considered in relation to France as a whole or even in relation to Europe, with the result that compensation between areas is not very likely, even though Mediterranean conditions may be quite different from those in the Atlantic. Meteorological data also indicate that wind may have a positive correlation with rain, which would be a considerable disadvantage; the coexistence of an extended period of dead calm with an extended period of drought would obviously present severe problems for a network such as that existing in France. /105

Since these general indications are relatively vague, a statistical study was undertaken on correlation of the power available at two meteorological stations (Saint-Inglevert and Perpignan) with the water power available in France in streamline form, such as is furnished by the hydraulic model.<sup>2</sup> This study

---

2. The "hydraulic model" reconstructs the total energy which would have been produced by all currently existing French hydroelectric generating plants if they had operated using the river flow rates as they have been measured on a monthly basis since 1921.



deals with monthly values (since the hydraulic model is on a monthly basis), computed for each month by planimetry of a curve of the cube of the classified wind speeds recorded from observations made each day at 7:00 hours, 13:00 hours and 18:00 hours.

Computations were made for each of the  $12 \times 14 = 162$  months from January 1926 to December 1939. The results are given in the form of three scatter diagrams: the first (Fig. 3) correlating Saint Inglevert and Perpignan; the second (Fig. 4) correlating water systems with Saint Inglevert; and the third (Fig. 5) correlating water systems with Perpignan.

Each point in each of these diagrams represents the events of a given month: the abscissa represents one of the energy values considered, and the ordinate represents the other. If there is a strong correlation between the two values the points in the diagram will be distributed along a line whose angular coefficient corresponds to the mean ratio of the two compared values.

Here, however, the diagram is extremely diffuse, and its configuration indicates that the correlation is extremely poor. On a first approximation it may thus be concluded that the wind is independent of water systems and that the wind at Perpignan is independent of the wind in the North. One may therefore rely on compensatory factors which are not systematic, but statistical.

The first conclusion, therefore: the quality of wind energy for a strongly water-dependent power supply network is characterized by an hourly as well as a seasonal variability without any systematic tendency capable of producing any great increase or decrease in the value of this variability in relation to that of a purely chance variability; there is little correlation among the variations at the different sites, at least between the ex-

treme north and the extreme south of France.

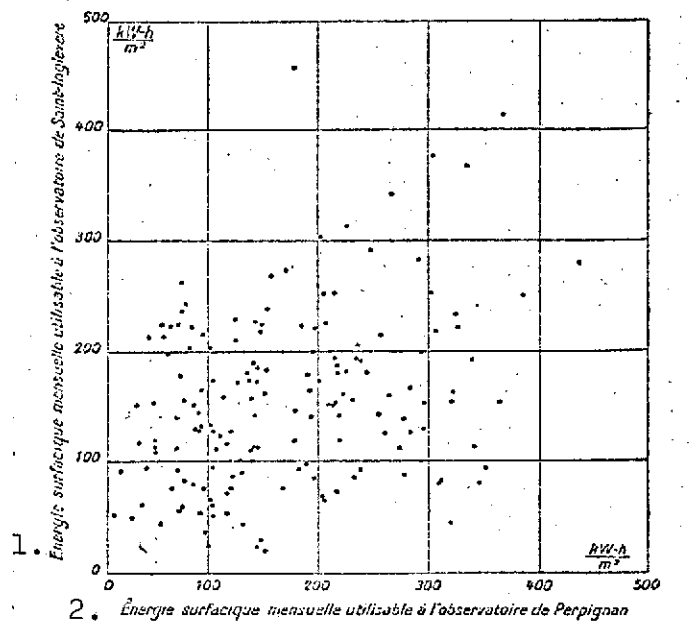


Fig. 3. Scatter diagram correlating the monthly energy values corresponding respectively to wind speeds measured at the St. Inglevert and Perpignan observatories during the period from January 1926 to December 1939. The monthly energy value for each of these locations was obtained for each month by planimetry of the curve of frequency of power available between 4 and 17 m/sec, these power values being assumed proportional to the cubes of the three instantaneous speeds occurring every day at these locations at 7:00 hours, 13:00 hours and 18:00 hours. These values have been furnished by the National Meteorological Office.

The values for the monthly surface energy of the wind expressed in kilowatthours have been determined using the formula

$P' = 0.3 \left( \frac{V}{10} \right)^3 \text{ kW} : \text{m}^2$ , which amounts to application of an efficiency of  $\frac{0.30}{0.37}$  to the theoretical energy recoverable by one wheel without distributor.

Key: 1. Usable monthly surface energy at St. Inglevert observatory.  
2. Usable monthly surface energy at Perpignan observatory.

#### IV. Amount of Energy Per Square Meter Available Annually

The amount of energy available annually will thus be the essential element permitting discrimination between sites.

Unfortunately, the speed of the wind depends to a considerable degree on its distance above the ground, and the variation above the ground is far from identical at the various sites. Now, the observatory anemometers are in general only 10 to 20 meters above the ground, that is, far below the presumed height of a wind engine, with the exception of the Eiffel Tower anemometer, which on the other hand is much too high.

Variations in wind speed as a function of the height above a completely flat terrain, such as has for example been determined on the pylons of the radio installations at Nauen and Einwese, follows a principle on the order of  $h^{0.2}$  to  $h^{0.3}$  in the interval with which we are concerned.

On a plain, the cube of the wind speed could therefore vary almost as quickly as the height.

On varied terrain, completely different principles apply. On cliffs, or even on ridges and hills, because of the contraction of air currents considerable speeds may be observed almost at ground level, which are analogous to those normally encountered only 100 meters above the ground.

This simultaneously opens the possibility that sites may be found where the wind will be extremely well-suited for use by a wind engine without the necessity of constructing a costly high tower, and raises some doubts as to the accuracy of conclusions obtained using data from meteorological stations.

These data, however, do at least reveal the configuration of power curves classified as a function of the time during which this power is available: the results for several sites are indicated in Fig. 6, where the ordinate is graduated according to the wind speed on a cubic rather than a linear scale, that is,

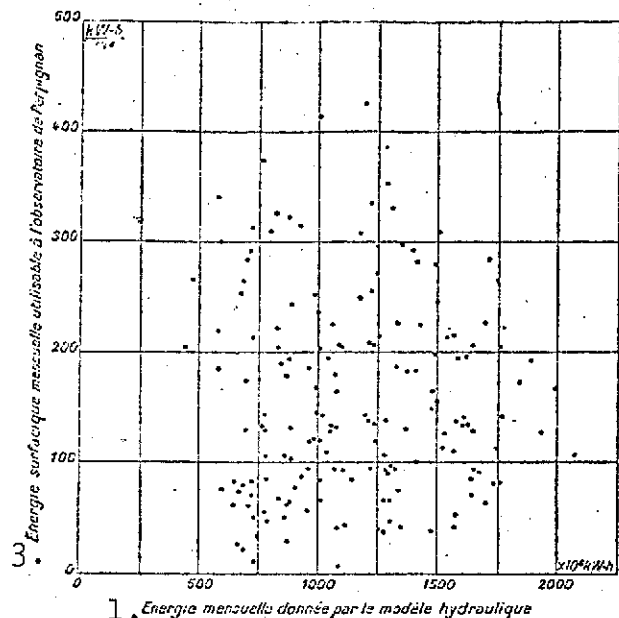
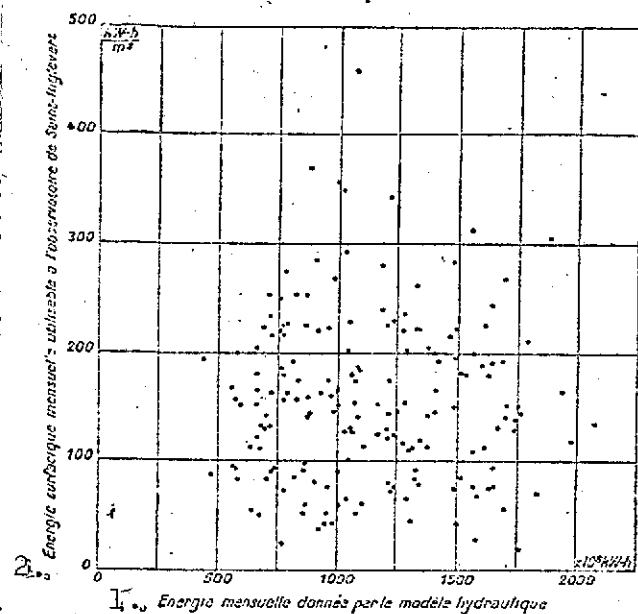
one proportional to the power available.

The wind engine, of course, will not be able to make use of wind below a certain speed, and its power will reach a peak above another given speed because of wear on the blades or other factors. The surface area between each curve and the axes of the coordinates, therefore, represents only a theoretical energy (Fig. 7). At this point, however, this is the best available criterion for comparison of sites, since the peak operational speeds of the wind engines will depend not only on the wind engine system itself, but also on the wind speed at the site for which the engine has been designed. There would thus be some risk in fixing these limits arbitrarily, and it is desirable to characterize a given site by the total energy available per surface unit.

/106

Inadequate distance from the ground is not the only difficulty encountered in using meteorological readings.

Wind measurements are of two types: (1) measurement of the instantaneous speed of the wind, which to be used must be converted into curves of the speeds cubed (appreciably changing their configuration) and must be planimetered, a procedure which is virtually impossible for long periods of time; (2) discontinuous instantaneous measurements, generally daily measurements at 7:00, 13:00 and 18:00 hours, which can easily be used for statistical studies, for example sorting punch cards by machine, but which give a relatively uncertain picture of wind activity during the course of the day.



Figs. 4 and 5. Scatter diagram correlating monthly energy corresponding to wind speeds measured at the observatories at St. Inglevort (left) and Perpignan (right) and that of a hydraulic model during the period from January 1926 to December 1939. The monthly energy at these locations was obtained by planimetry for each month of the curve of frequency of power available between 4 and 7 m/sec, the power values being assumed proportional to the three instantaneous speeds cubed, measured each day at this site at 7:00, 13:00 and 18:00 hours; these values supplied by the National Meteorological Office.

- Key: 1. Monthly energy given by hydraulic model.  
 2. Usable monthly surface energy at St. Inglevort observatory.  
 3. Usable monthly surface energy at Perpignan observatory.

#### V. Device for Gaging Wind Power

For all these reasons it appeared not only that meteorological data would be insufficient for estimating the energy value available annually per square meter of wind engine surface, but also that selecting sites by installing new anemometric stations of the classical type would be extremely difficult and costly, while only relatively uncertain results would be obtained.

Two years ago we therefore proposed to select sites by means of devices directly integrating the cube of the wind speed, that is, giving the energy per square meter. These consisted of an

anemometer adaptable to what was virtually a miniature wind engine capable of supplying the power required to activate a special electric meter.<sup>3</sup>

Taking periodic meter readings does not entail the restrictions and the risk of error inherent in the use of a recording device by the unspecialized personnel likely to be available at the most favorable locations. There is no risk of failure to record at critical moments because of a lack of paper or ink or an absence of measurement regularity. A direct result is obtained without the added complication of using planimetry on such a variable function.

Thus defined, the problem was presented to the Company for the Manufacture of Gas Company Meters and Equipment, which provided a solution in the form of a non-directional anemometer derived from the Robinson anemometer which drives an alternating generator with a permanent magnet whose voltage and frequency are proportional to the wind speed. This voltage simultaneously powers the two windings of the meter, and it is possible to give values to the circuit constants such that the meter will integrate the cubes of the speeds.

A prototype of this device (Figs. 8 and 9) weighing 30 kilograms can easily be affixed to the top of a pylon, pole, etc. A connecting cable makes it possible to lower the meter to the ground to facilitate readings.

The device is graduated directly in kilowatthours per square meter using the numerical formula:

- 
3. This comparison should not be taken literally in regard to the actual physical set-up: in actual fact, the anemometric device must virtually race in order to transmit an amount of power to the meter which is insignificant in relation to the power recoverable on the same surface. This electrical arrangement gives the meter a rotation speed proportional to the wind speeds cubed.

$$P = 0.37 \left( \frac{V}{10} \right)^3$$

where P is the surface power in kilowatts per square meter, and  $\frac{V}{107}$  V is the wind speed in meters per second.<sup>4</sup>

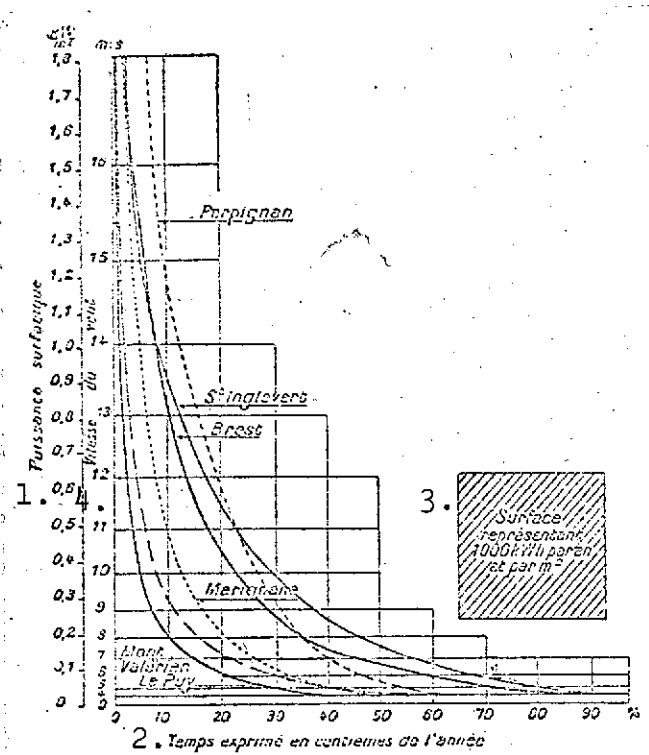


Fig. 6. Curves of wind speeds and power values at various sites, classified according to the frequencies of various wind speeds measured at 7:00, 13:00 and 18:00 hours during the period from January 1926 to December 1939.

The surface energy of the wind in kilowatts per square meter was determined using the formula  $P = 0.37 \left( \frac{V}{10} \right)^3 \text{ kW} : \text{m}^2$ .

- Key: 1. Surface energy. 3. Surface representing 1,000 kWh per  $\text{m}^2$  per year.  
2. Time expressed in hundredths of a year. 4. Wind speed.

4. That is, in air with a specific density  $\rho$  with a speed V activating a wind engine sweeping a surface area S. This wind engine is unable to make integral use of the kinetic energy passing through it, if only because the air which has performed its work must be expelled. It can be shown that the maximum usable energy is given by the formula

$$P = \frac{16}{27} \times \frac{1}{2} \rho S V^3.$$

The formula in the text corresponds to air with a specific density  $\rho = 1.25 \text{ kg/m}^3$ .

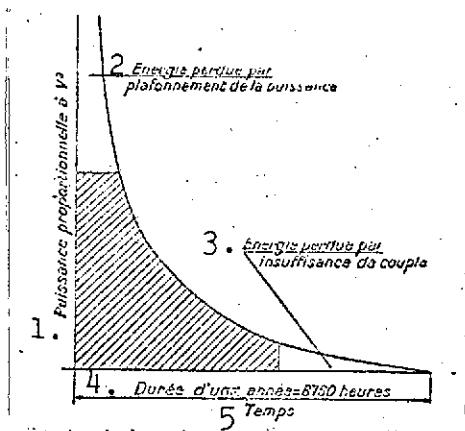


Fig. 7. Curve of power proportional to cube of wind speed, as a function of time expressed in hours.

- Key: 1. Power proportional to  $V^3$ .  
 2. Energy lost by attainment of peak power.  
 3. Energy lost by insufficient torque.  
 4. Length of one year = 8,760 hours.  
 5. Time.

Actual wind engines, of course, will be subject to a coefficient of imperfection in relation to this value which should not be underestimated, given the variability of wind; the size of this coefficient is currently very difficult to calculate. An imperfection coefficient of 70 percent would perhaps be a reasonable provisional evaluation.

The Organizational Committee for Electrical Energy has ordered 150 of these devices to be delivered June 1, 1946. The Minister of the Colonies has also ordered a series of 100.

The prototype has undergone wind tunnel testing. After adjusting the mechanism it was impossible to produce breakage by centrifugal force; and still greater resistance was offered to the maximum speed of the Hispano-Suiza wind tunnel, that is 50 m/sec = 180 km/hr, which corresponds to pressures exceeding those projected by the technical plan by 30 percent.

It is not certain that this device would be able to last indefinitely in areas where there are exceptionally violent winds, for example on Mt. Ventoux or in certain colonial locations. Breakage of the windmill is not serious, however, and it was much more important that the device be light enough to retain its precision and starting facility at normal sites.



The calibration curve for the device shows that it follows the cubic principle, except at very low speeds; the device will start fairly regularly at a speed on the order of three meters per second, which is enough to overcome the magnetic attraction of the alternator poles. Once the device has started, this magnetic attraction disappears, its average value per rotation being nil.

At very high wind speeds, the readings of the device fall below the cubic functions; however, wind occurs too infrequently at these speeds to represent any appreciable amount of energy per year; thus these winds would be virtually impossible to use. Error due to high winds is also without any great importance, therefore, especially if the sites are being compared using identical devices.

#### VI. Objective and Gaging Method

The objective of this gaging process is in fact quite limited: this is a matter of comparing measurements in order to make a fairly rapid determination, in two or three years, of the sites which appear to be best suited to a wind device. More complete anemometric installations could then be furnished for these sites which would give recording charts of the cubed speeds, possibly with separate charts for high and low winds. There will undoubtedly be a more detailed study of wind structure on a time scale appropriate for airscrews, so as to determine the maximum stresses to which these wind engines will be subjected.

For the present, however, it will be necessary only to make parallel comparative measurements at a fairly large number of sites, using unspecialized personnel.

It may be assumed that the meters could be read once a week, in view of the studies dealing with correlation with water power.

## VII. Gaging Stations.

These devices will of course be installed in all the meteorological stations which currently have relatively old data available. Thus, after an adequate reconciliation of the power measurements with the average speed measurements from the meteorological stations, it will be possible to use the older data from these stations and thus to extend our experience over a greater number of years. This is important for a study of the deviations between years and exceptionally low water levels.

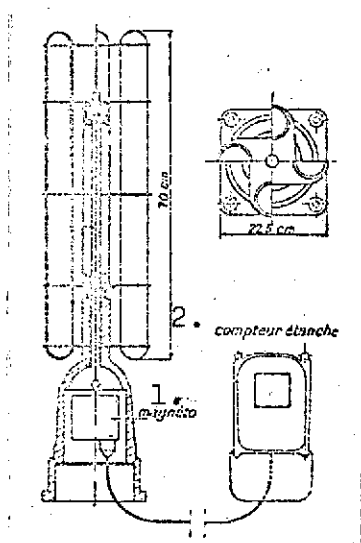


Fig. 8. Sketch of the anemometric device combined with an electric meter which gives direct information on the surface energy available, in kilowatthours per square meter of surface subjected to wind action.

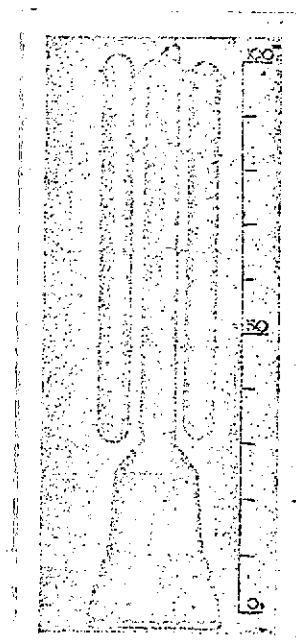


Fig. 9. View of the anemometric device.

Key: 1. Magnét.  
2. Watertight meter.

Furthermore, at a few locations selected because of the available personnel, daily readings taken in the morning and the evening will make it possible to determine the ratio of day to night energy production. Attempts will also be made to determine whether this ratio differs from one season to the next, from a

period of high winds to one of low winds, from a period of turbulence to one of laminar wind flow, and according to the distance from the ground.

It is particularly important to determine the variation in power as a function of the height above ground, since this variation principle could influence selection of the diameter and height of the wind engines. Moreover, it is not easy to find sites which lend themselves to measurement at two points, both of them completely clear of obstacles, and with no practical differences between them except for their elevation. Radio installations do have these characteristics, and will furnish data on variations in energy according to height on flat terrain. To obtain information on the same variations when wind is passing over a cliff, a comparison might be made between measurements taken atop a lighthouse and measurements taken from the top of some lower support which should be fairly nearby in order to be in the same wind system, and yet far enough away so as not to be influenced by the ripples created by the lighthouse structure.

The remainder of the 130 devices will be distributed among the transporters and distributors of electrical energy located in those areas which appear to have favorable characteristics a priori: the coast along the English Channel and along the ocean; the plateaux of Limousin (using the high pylons in Paris for 220 kV lines supplying the Central Massif) and of the Causse; the wide corridors of the valley of the Rhone (on the plains, at Mt. Ventoux, at the borders of Cevennes and at Aigoual) and of the Naurouze shelf; the plains of Flanders (Cassel) and Beauce, which are highly exposed to the wind, etc.

Of course, only those sites should be used which already possess a structure permitting installation of the device at an adequate height above the ground to furnish usable information,

that is at least 20 or 25 meters.

The data supplied by these stations will be centralized in a form permitting its future use on punch cards in a series of studies correlating these data with water power possibilities, the marginal kilowatthour values produced in thermal plants, etc.

After a fairly short period of about one or two years it will probably be possible to eliminate, by comparison, a certain number of poorly suited sites and to transport the devices thus made available to these areas recognized as most favorable, or to those which were not taken into consideration initially.

Thus in a short period of time an initial contribution may be made to the problem of the amount of wind energy per square meter which is available annually, a contribution resting on a well-defined and unquestionable technical basis.